Hurricanes and global climate change

- ☻ What role do hurricanes play in climate?
- ☻ Why do hurricanes exist?
- ☻ Why are there order 84 tropical cyclones per year?
- ☻ How should hurricanes change as climate changes?
- ☻ Are models adequate?
- ☻ What is the role of global warming?
- ☻ Damage prospects

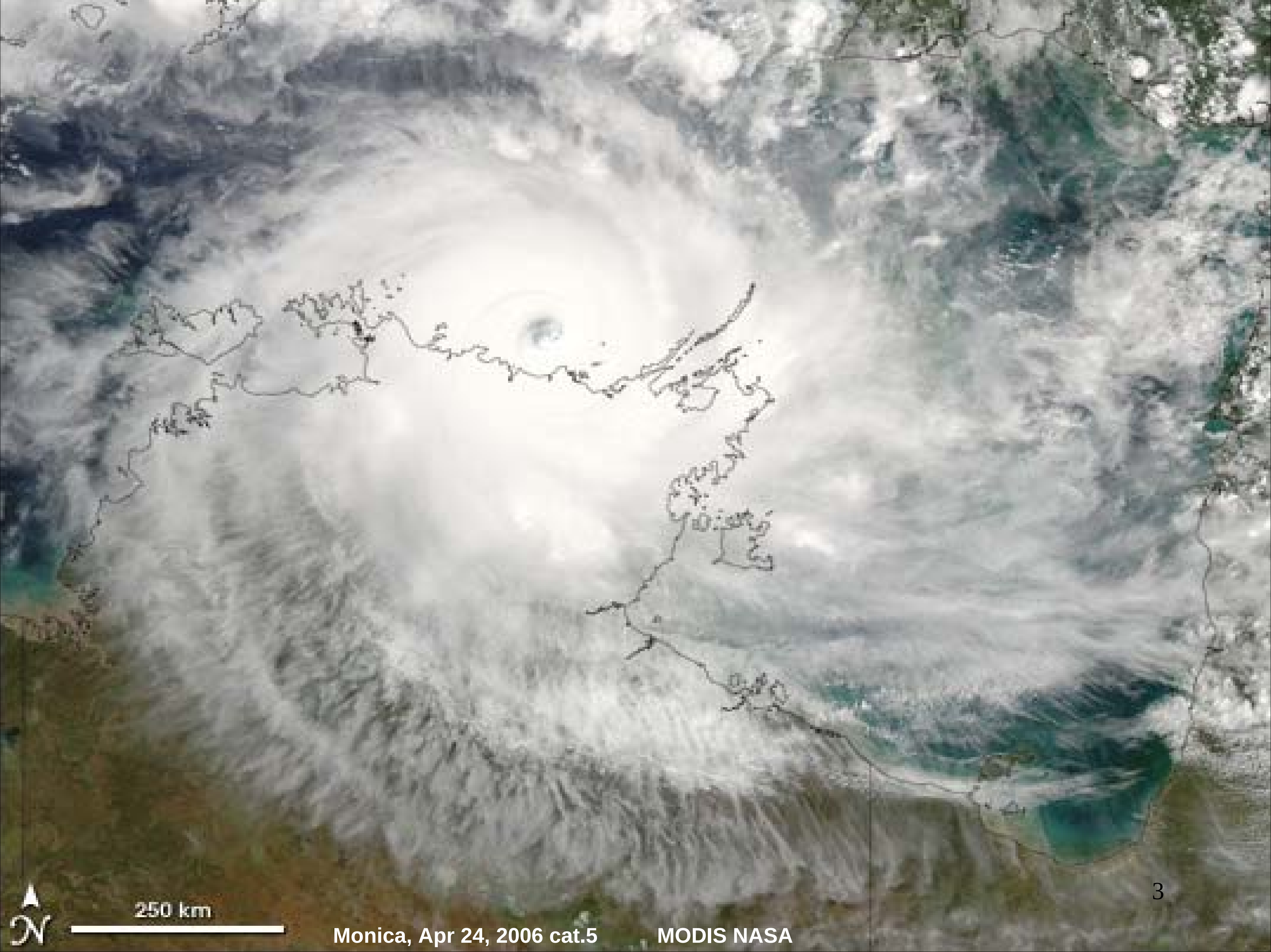
- The record breaking 4 hurricanes that hit Florida in 2004
- The record number of tropical storms in the Atlantic in 2005
- The first hurricane in S. Atlantic (Catarina) March 2004
- The record damage from Katrina:

Lead us to ask:

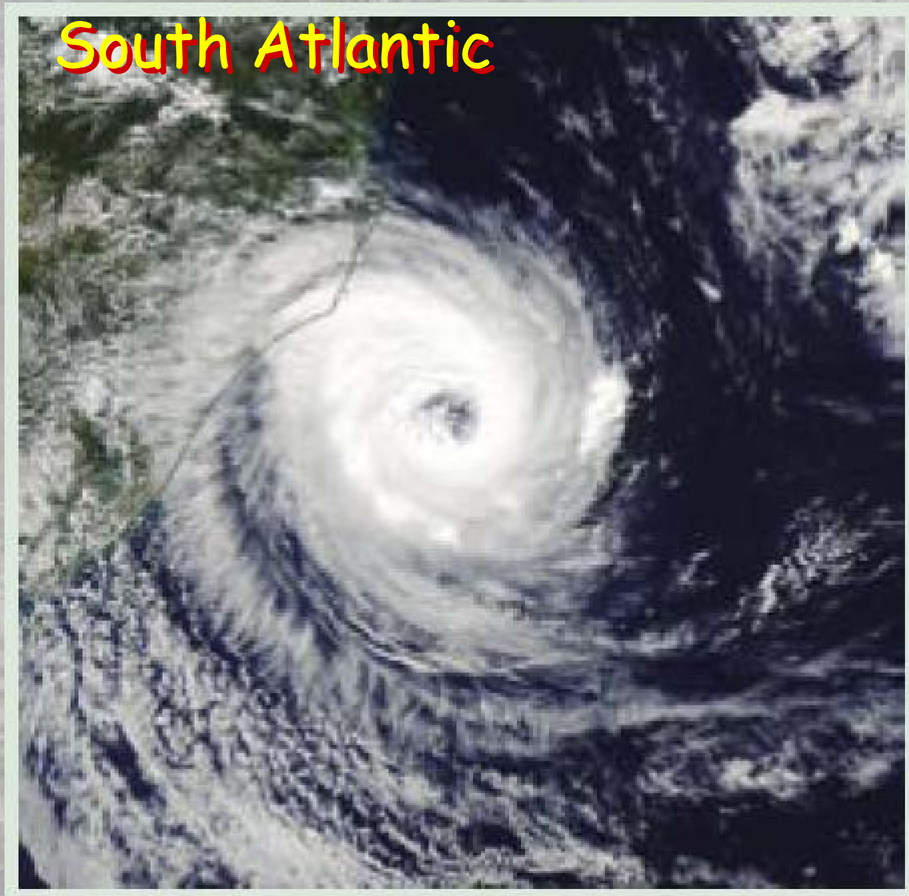
Are hurricanes changing with global warming?

Kevin E Trenberth

With support from
Dennis Shea and Chris Davis



Monica, Apr 24, 2006 cat.5 MODIS NASA



Catarina

First and only (known) hurricane in South Atlantic

Satellite image at 16:30 UTC on 24 March 2004 of cyclone "Catarina" over the South Atlantic Ocean, from the afternoon overpass of NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra satellite.

North Atlantic Hurricanes 2005
A record breaking year:

- Strongest Gulf hurricane month of July (Dennis)
- Most named storms (27*)
- Most hurricanes (15)
- First ever V, W, α, β, γ, δ, ε, ζ
- Strongest hurricane on record: Wilma (882 mb)
- Strongest hurricane in Gulf: Rita (897 mb)
- Most cat. 5 storms in season (3 vs 2 in 1960,1961)
- Deadliest hurricane in US since 1928 (Katrina)
- Costliest natural disaster in US history (Katrina)
  - Highest insured losses ~$40-60B vs Andrew $21B
  - Total losses ~$125-200B
  - 6 of the 8 most damaging occurred Aug 04-Oct05
    Charlie, Ivan, Francis, Katrina, Rita, Wilma
- Hurricane Vince (October) first to hit Portugal/Spain

Hurricanes:

- ☻ Depend on SSTs > 26°C (80°F)
- ☻ High water vapor content
- ☻ Weak wind shear (or vortex comes apart)
- ☻ Weak static stability
- ☻ Pre-existing disturbance

Large variability year to year in individual basins.

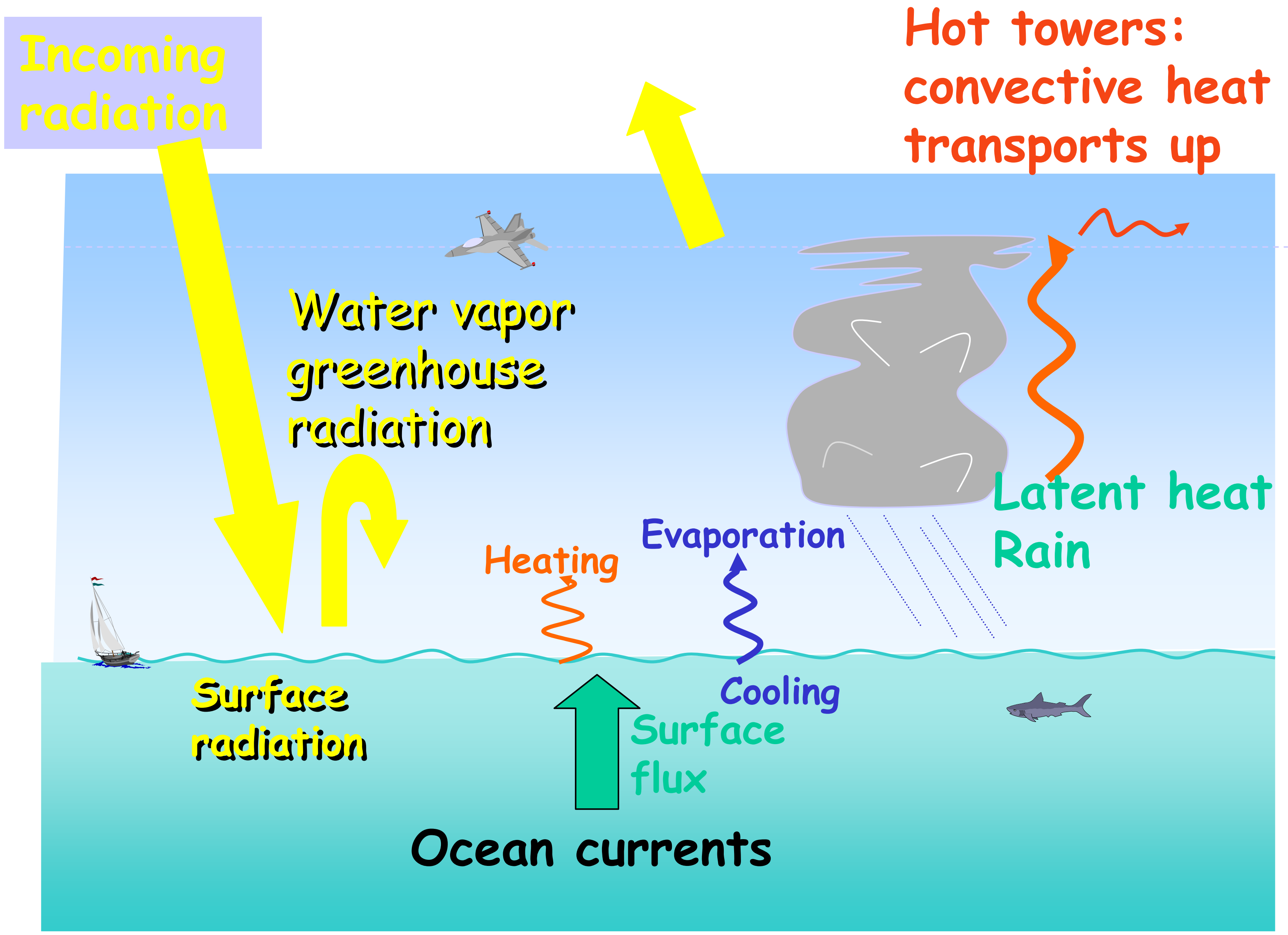
El Niño means more action in Pacific, suppression in Atlantic

Large decadal variability in Atlantic

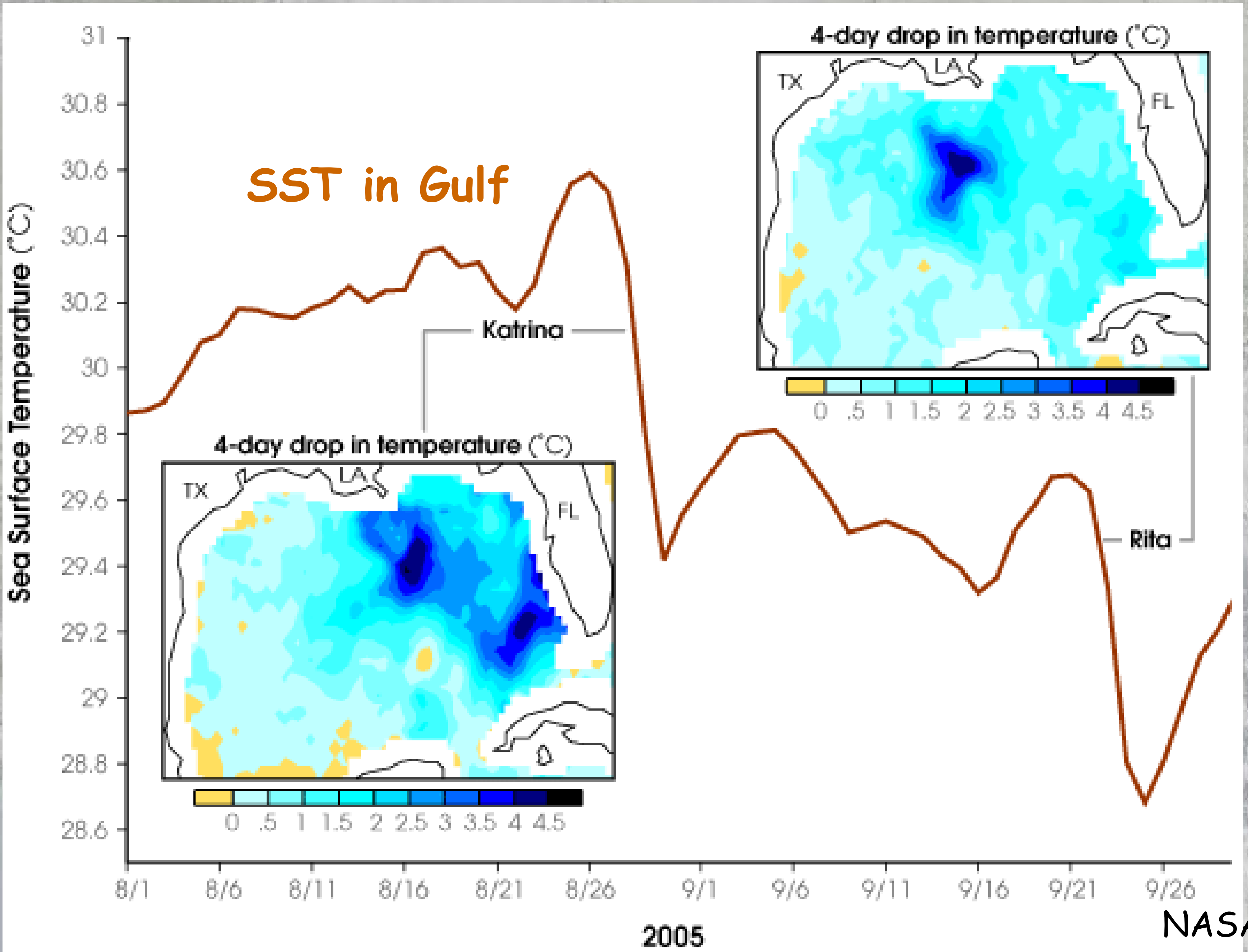
In the tropics, heat from the sun goes into the ocean and is apt to build up: Where does the heat go?

1) **Surface heat cannot radiate to space** owing to optically thick water vapor
2) **Heat goes from the ocean into the atmosphere** largely through **evaporation** that is greatly enhanced in tropical storms. It **moistens** the atmosphere **(latent energy)** and cools the ocean.
3) **Heat and moisture are transported to higher latitudes** by extratropical cyclones and anticyclones (cold and warm fronts) mainly in winter.
4) **Heat is transported upwards:** in convection, especially thunderstorms, tropical storms, hurricanes and other disturbances. Energy and moisture from the surface is moved upwards, typically producing rain, drying the atmosphere, but heating it, and stabilizing the atmosphere against further convection.

Tropical ocean heat balance



Cold wake from Katrina and Rita in Gulf of Mexico

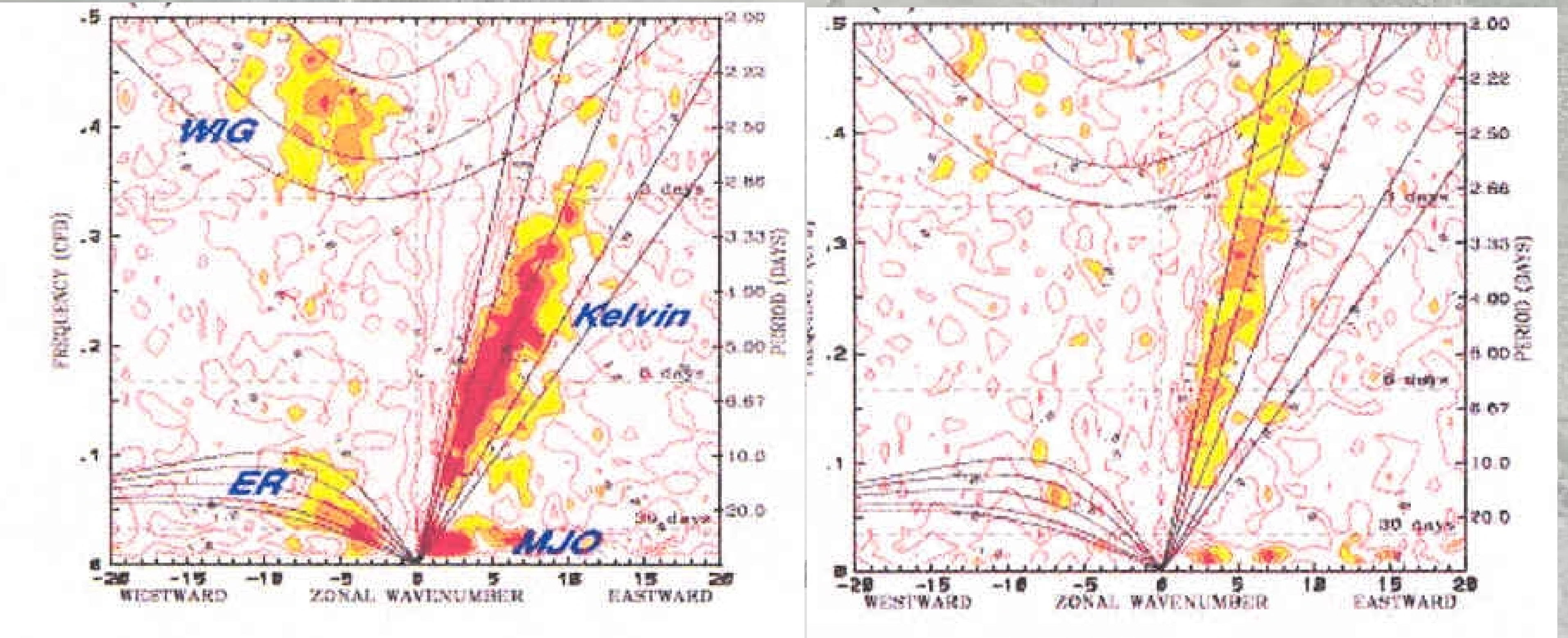


NASA

In the tropics, heat from the sun is apt to build up:

4) There is a **competition** between individual thunderstorms and organized convection to transport heat upwards in the general atmospheric circulation.
5) Tropical storms are much more effective at cooling the ocean.

6) In models, the thunderstorms and convection are not resolved and are dealt with by "**sub-grid**" scale parameterization.
7) However, most (all?) climate models have **premature onset of convection**, as seen in the diurnal cycle over land, and feature convection too often and with insufficient intensity.

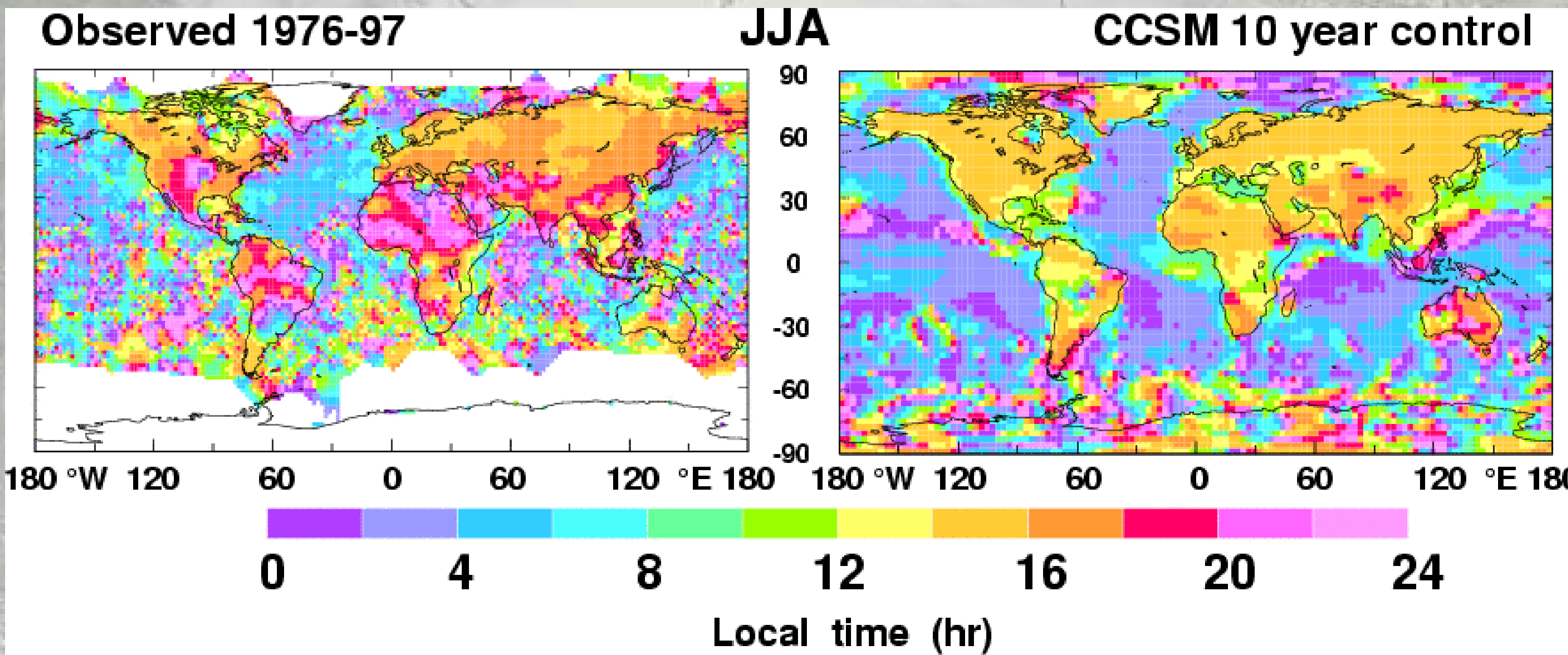


Space-time spectrum of the 15N-15S symmetric component of precipitation, divided by the background spectrum; Observations (left) and CCSM (right). Note the poor simulation of the Kelvin and MJO modes and the nearly non-existence of the Rossby (ER) and the Inertial Gravity (WIG) modes. The poor representation of moist convective processes is a major factor.

Lin et al 2006, J Climate submitted

Diurnal Cycle of Convective Precipitation for JJA

Time of maximum



Modeled frequency occurs about 2 hours earlier than observed

Trenberth et al. 2003

Model deficiencies

8) As models feature convection too frequent and without adequate intensity, it is likely that sub-grid scale convection is **overdone** at the expense of organized convection (MJO, tropical storms etc).

9) Hence models likely **under-predict** changes in hurricanes.

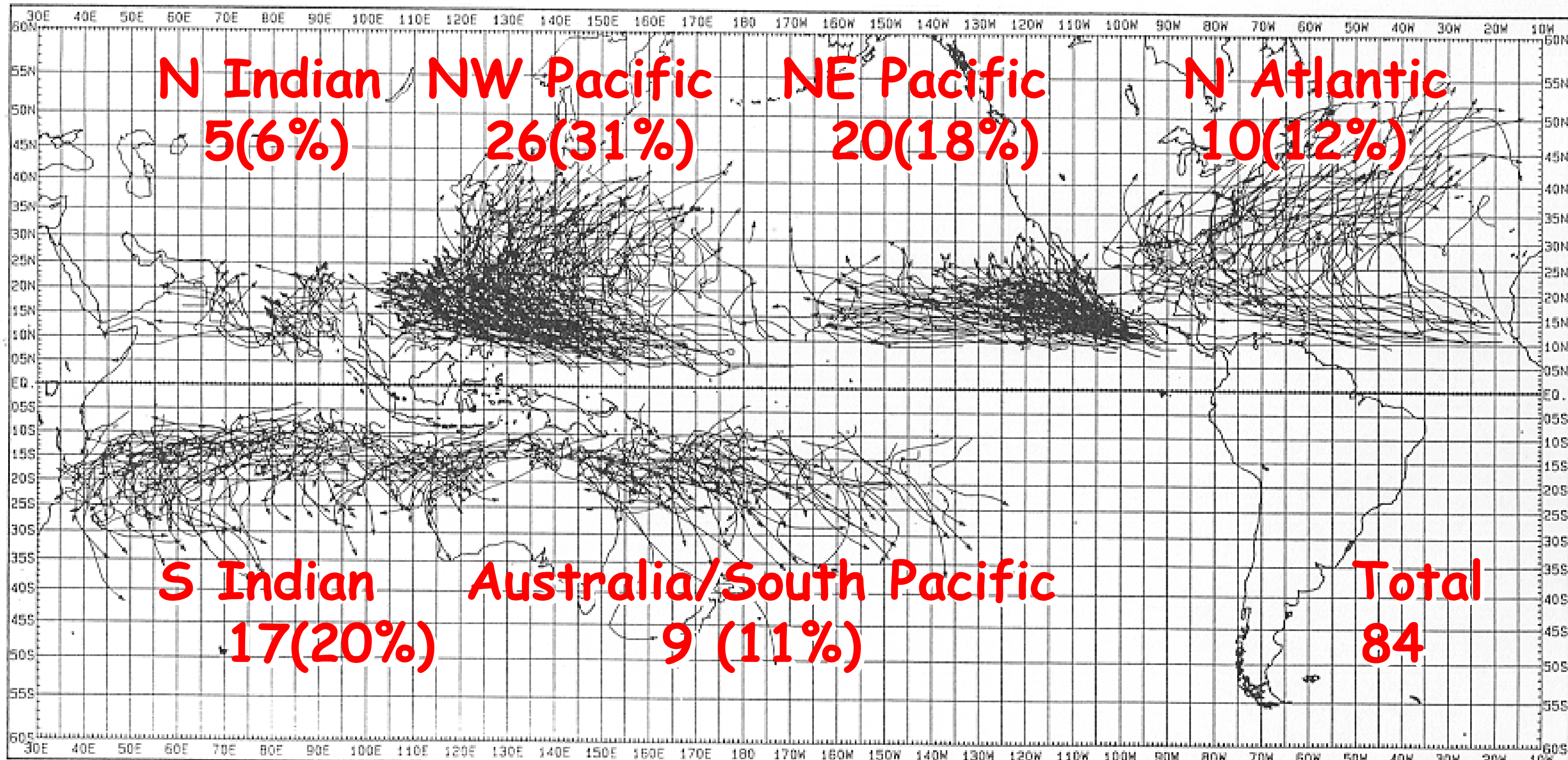
10) Climate models do not contain hurricanes: does that mean the SSTs are too warm in future climates?

Hypothesis:

Hurricanes play a key role in climate, but are not in models and not parameterized.

Prospects are for more intense storms, heavier rainfalls and flooding, and coastal damage, but perhaps lower tropical ocean temperatures?

The N Atlantic is only 12% of total tropical storms

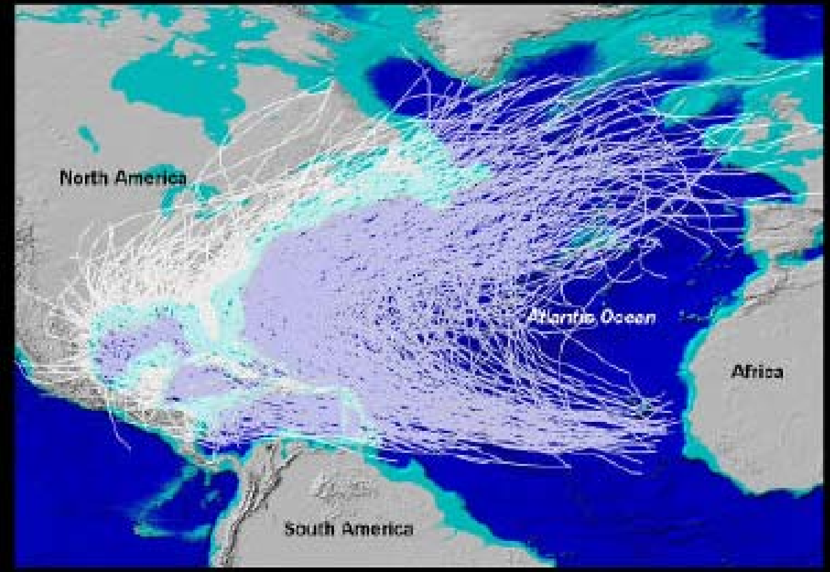


Tracks of tropical cyclones
with winds >34 kt for 1979-1988

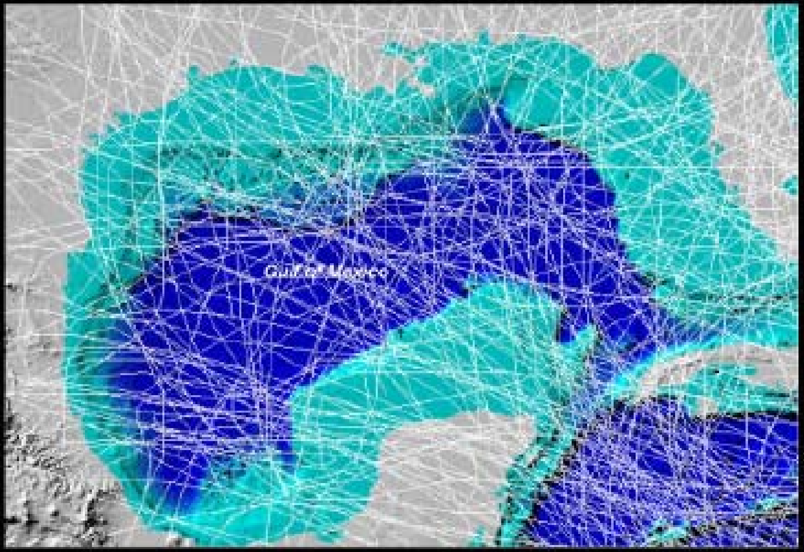
Issues on changing damage from hurricanes

Landfalling hurricanes are a very small fraction of all hurricanes and the sample is small. Where they make landfall is chance and 10 miles (e.g., Andrew) can make a huge difference to damage.

The increased vulnerability of people with increased property value building in coastal zones, placing themselves in harms way, makes changes in hurricane intensity even more important.



North Atlantic Hurricane 'Tracks' 1886-1996 from NOAA NHC



Gulf of Mexico Hurricane 'Tracks' 1886-1996 from NOAA NHC

100 years of tropical storm tracks in Atlantic

Global Warming is happening

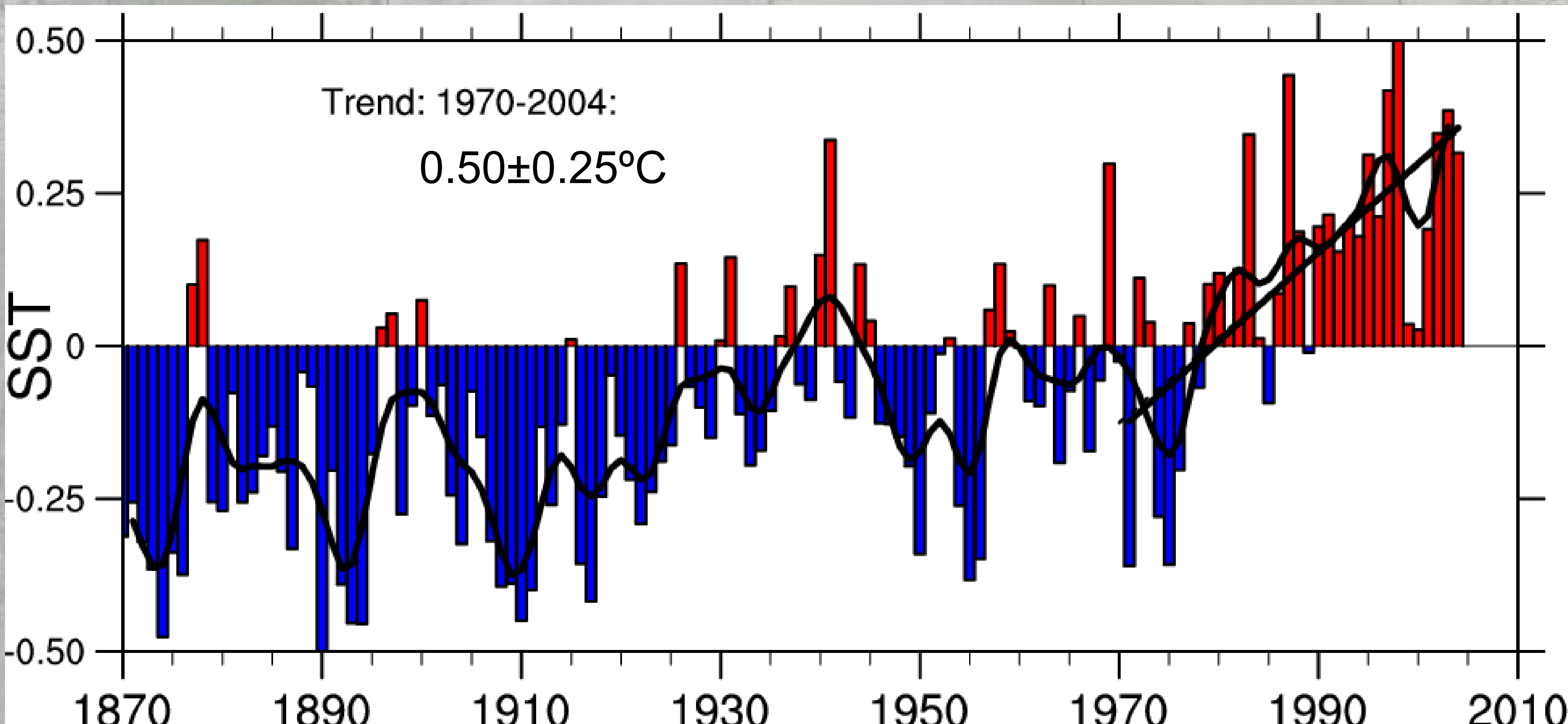
Since 1970, rise in:

- Carbon Dioxide
- Global temperatures
- Global SSTs
- Global sea level
- Tropical SSTs
- Water vapor
- Rainfall intensity
- Precipitation extratropics
- Hurricane intensity
- Drought

Decrease in:

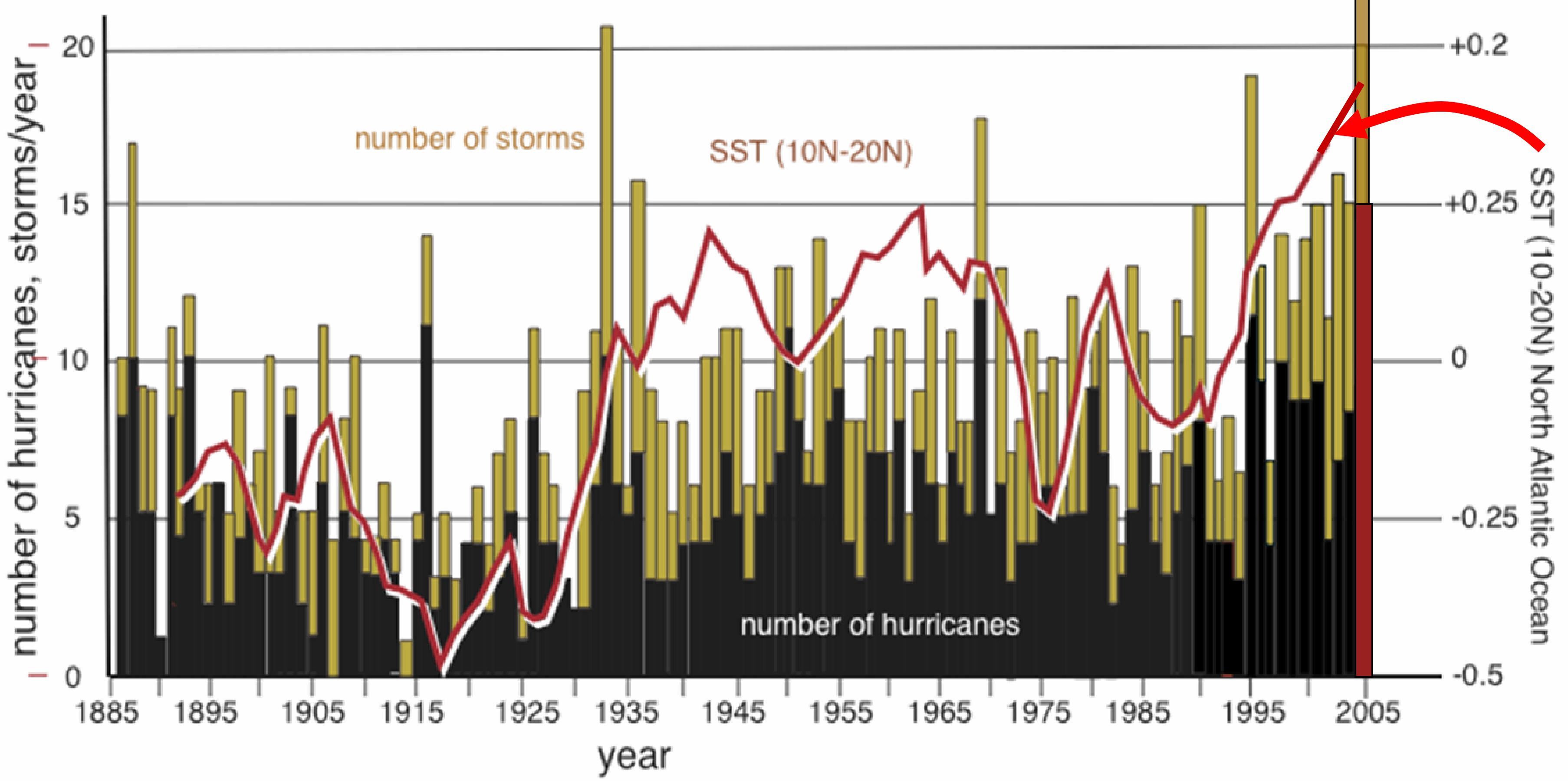
Snow extent

Arctic sea ice



SST in the tropics 20N-20S relative to 1961-90 mean: annual means and low pass filter values to emphasize decadal variations.

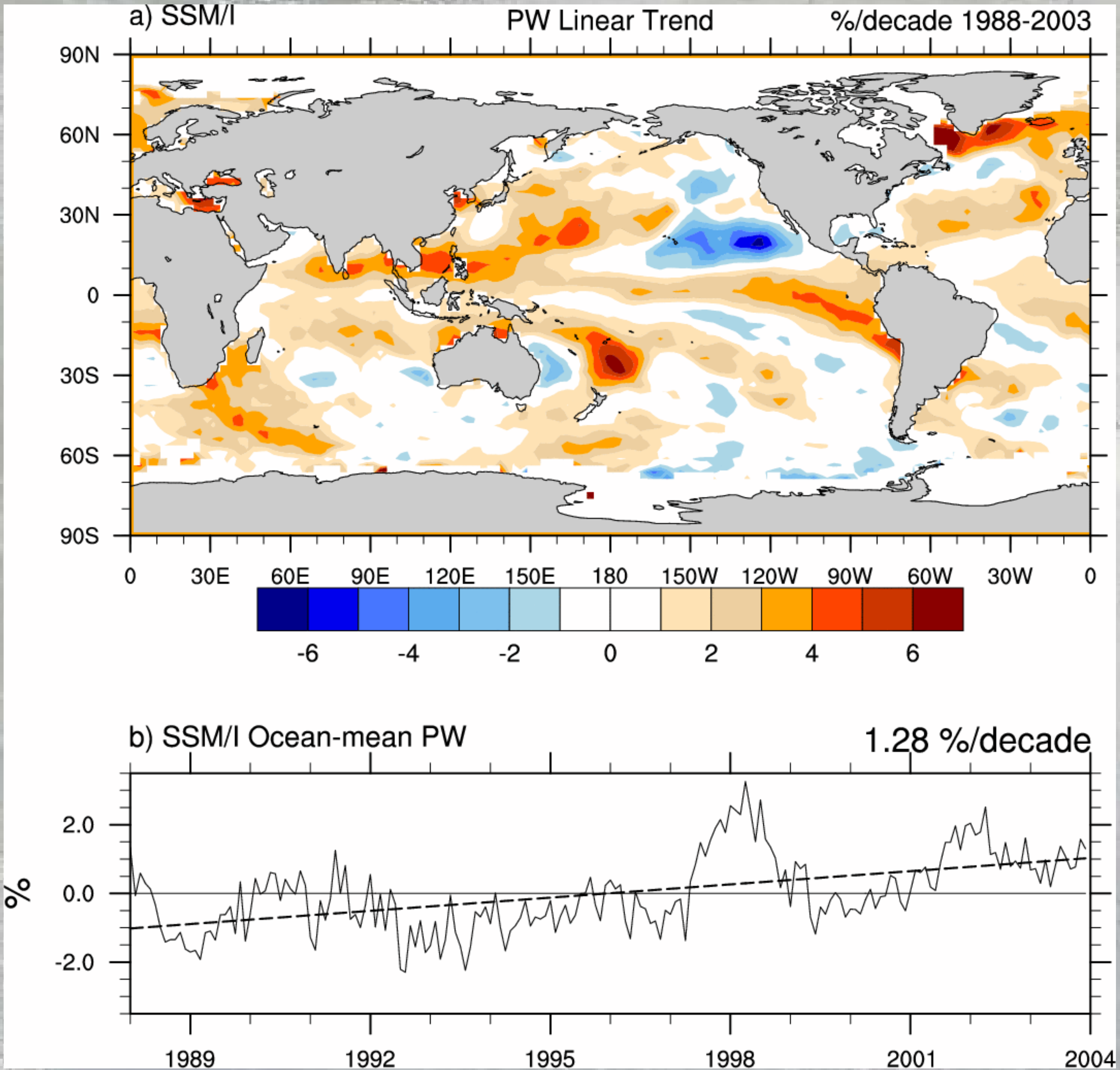
Changes in hurricane frequency in the North Atlantic Ocean



Water Holding Capacity

A basic physical law (the Clausius-Clapeyron equation) tells us that the water holding capacity of the atmosphere goes up at about 7% per degree Celsius increase in temperature (global value).

In the Tropics at the surface the best value is about 6%; or 7 to 8% per K of SST.



Total column water vapor is increasing:
Best estimate of linear trends:

Global ocean 1.3±0.3% per decade

Sig. at >99%

Trenberth et al 2005

Hypothesis on effects from global warming

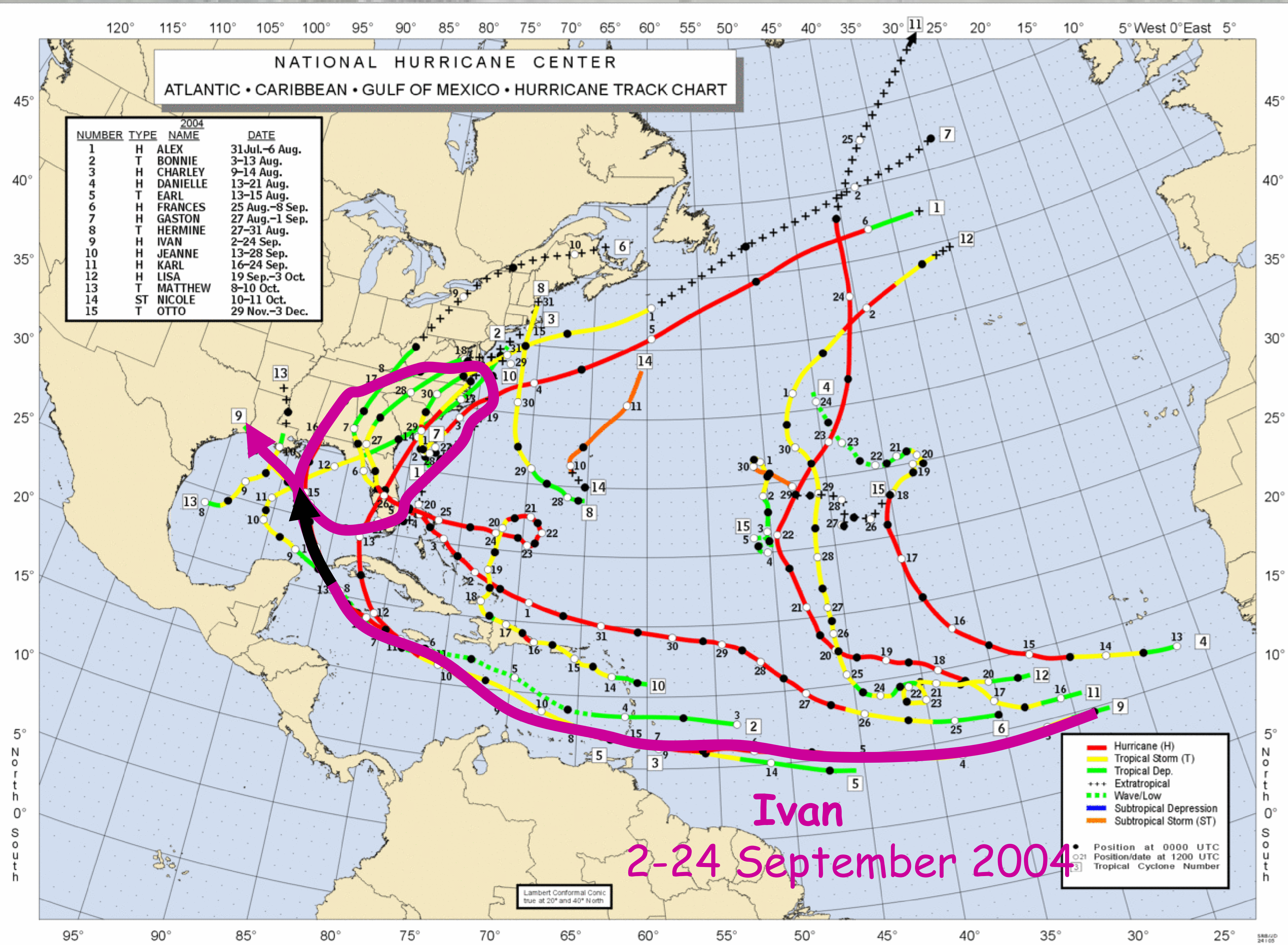
Water vapor over oceans increases ~7% per K SST

- To first order, surface latent heat fluxes also increase by at least this amount as $E \approx \rho C V q_s(Ts)(1-RH) \sim q_s(Ts)$
- Convergence in boundary layer also should go up proportionately. [$q\Uparrow$, $\omega\Uparrow$, $v_r\Uparrow$ **and $v_r.q\Uparrow$ squared**]
- Could also increase intensity: V
- Other feedbacks (friction, sea spray, stability etc)

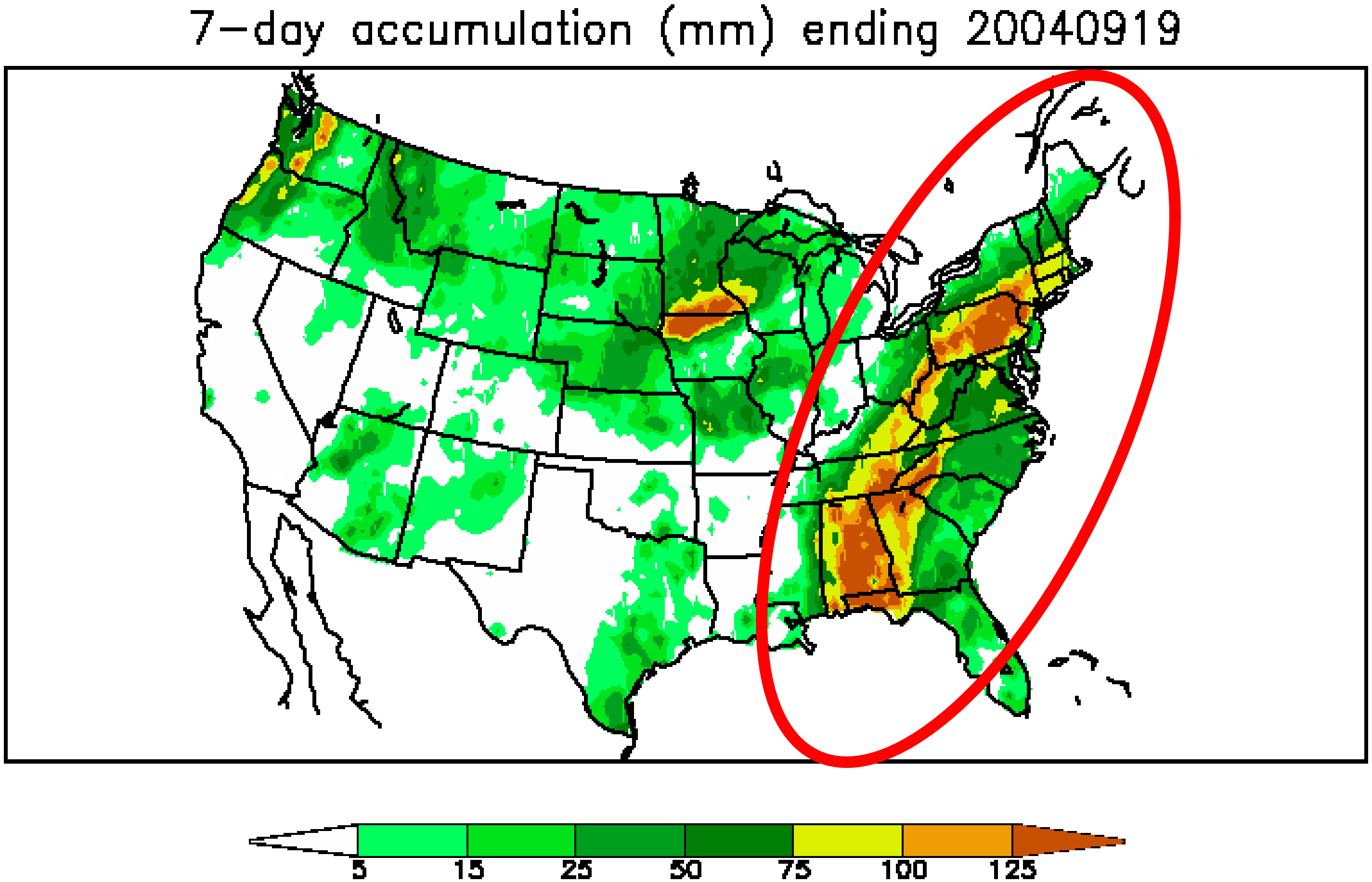
Hence estimated rainfall, latent heating and water vapor in the storms should increased $1.07^2 = 1.14$ or 14%. [7 to 21% error bars] per K.

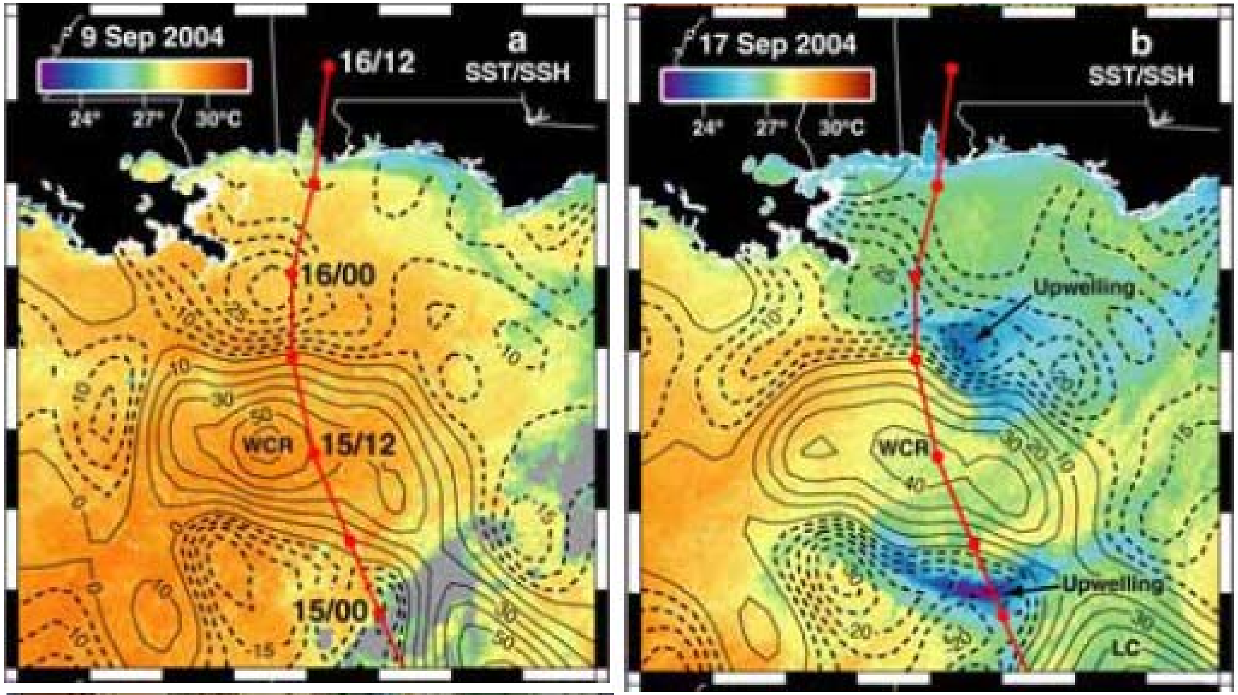
For observed 0.5K increase in SST this means increases in rainfall and latent heat release in storms by order 7%.


Image courtesy of MODIS Rapid Response Project at NASA/GSFC
Ivan
15 Sept 2004
1850 UTC
A case study

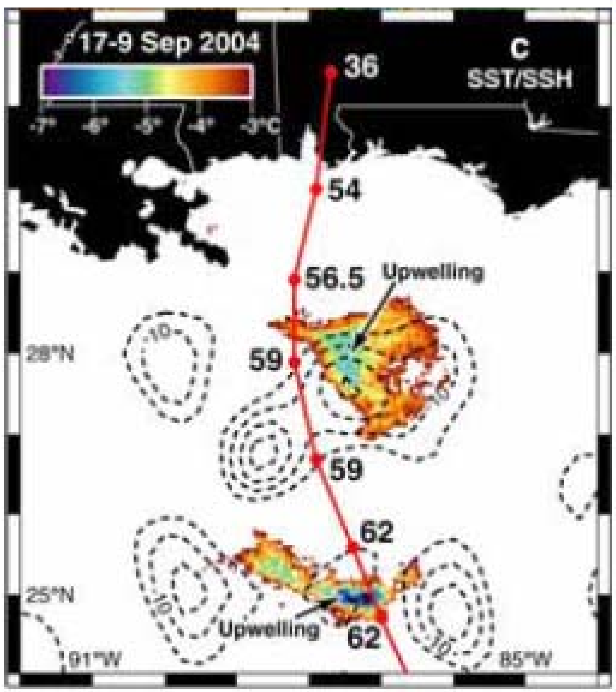

NATIONAL HURRICANE CENTER
ATLANTIC • CARIBBEAN • GULF OF MEXICO • HURRICANE TRACK CHART
2004
NUMBER TYPE NAME DATE
1 H ALEX 31 Jul.–6 Aug.
2 T BONNIE 3–13 Aug.
3 H CHARLEY 9–14 Aug.
4 H DANIELLE 13–21 Aug.
5 T EARL 13–15 Aug.
6 H FRANCES 25 Aug.–8 Sep.
7 H GASTON 27 Aug.–1 Sep.
8 T HERMINE 27–31 Aug.
9 H IVAN 2–24 Sep.
10 H JEANNE 13–28 Sep.
11 H KARL 16–24 Sep.
12 H LISA 19 Sep.–3 Oct.
13 T MATTHEW 8–10 Oct.
14 ST NICOLE 10–11 Oct.
15 T OTTO 29 Nov.–3 Dec.
Hurricane (H)
Tropical Storm (T)
Tropical Dep.
Extratropical
Wave/Low
Subtropical Depression
Subtropical Storm (ST)
Position at 0000 UTC
Position/date at 1200 UTC
Tropical Cyclone Number
Lambert Conformal Conic true at 20° and 40° North
Ivan
2-24 September 2004

Rainfall from hurricane Ivan





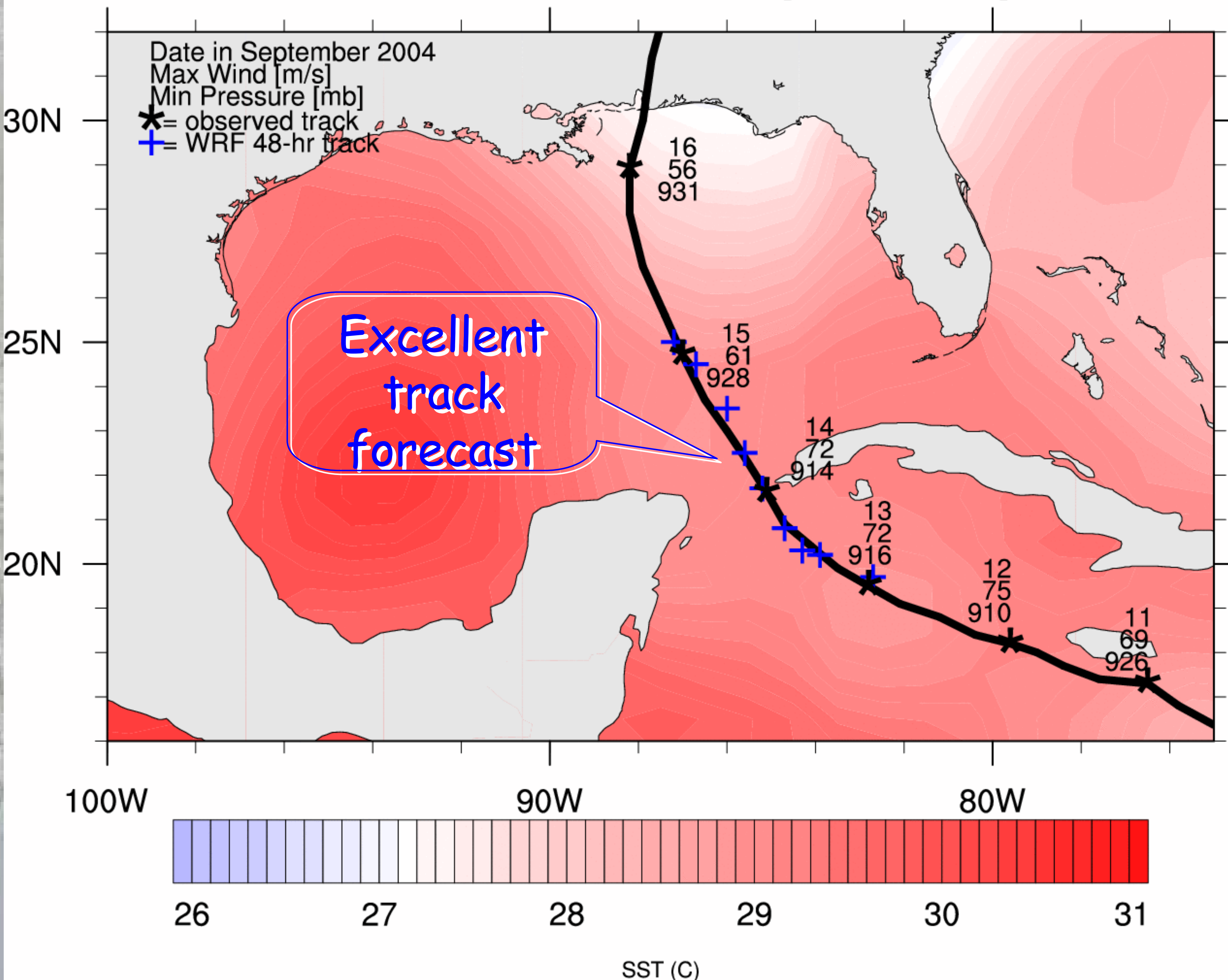
Loop Current:
SSH +ve is anticyclonic eddy.



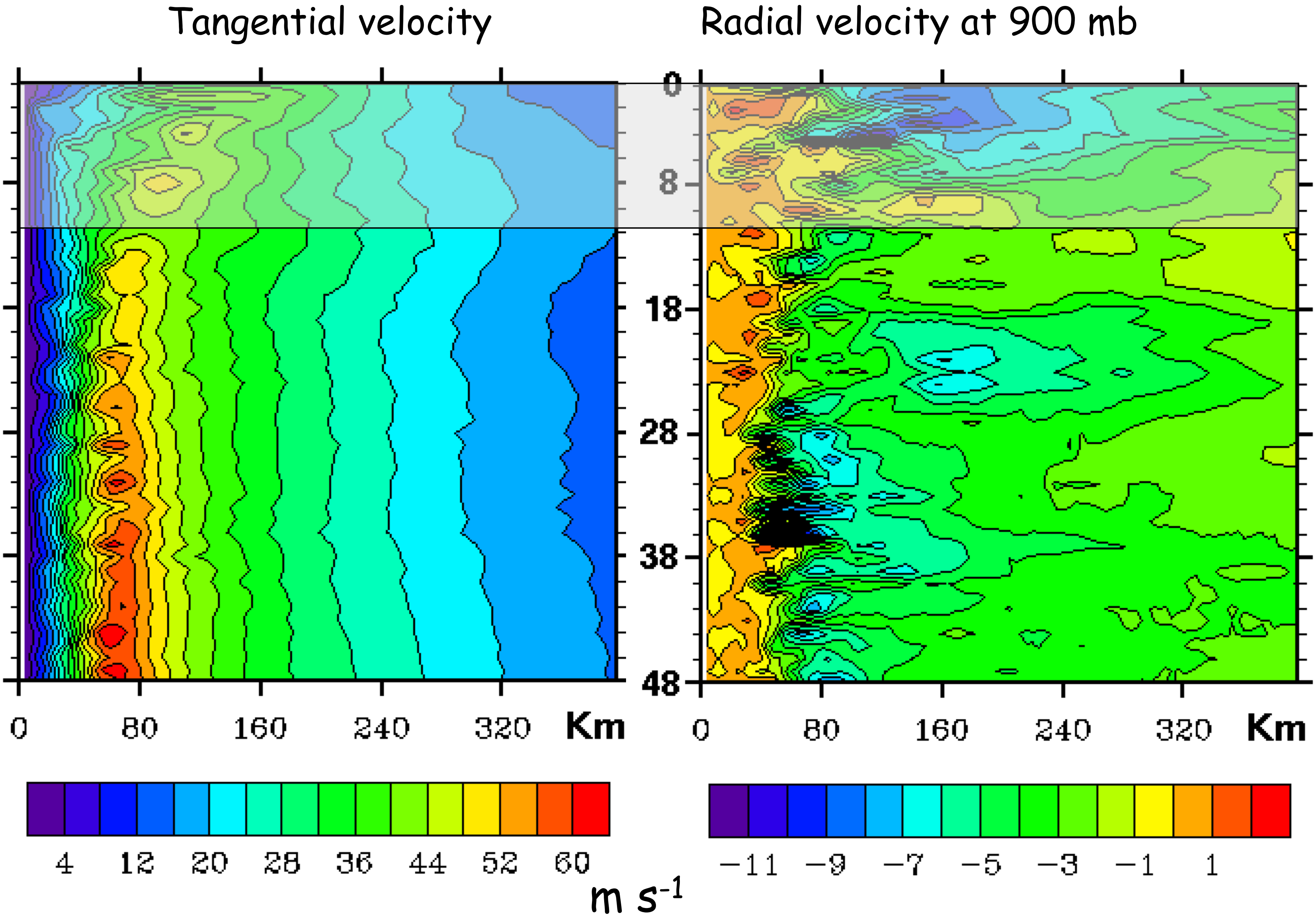
Hurricane Ivan:
15 September 2004
SST and SSH before (9th) and after (17th) with differences of SST > 3°C and SSH > 5 cm

Walker et al. 2005 GRL

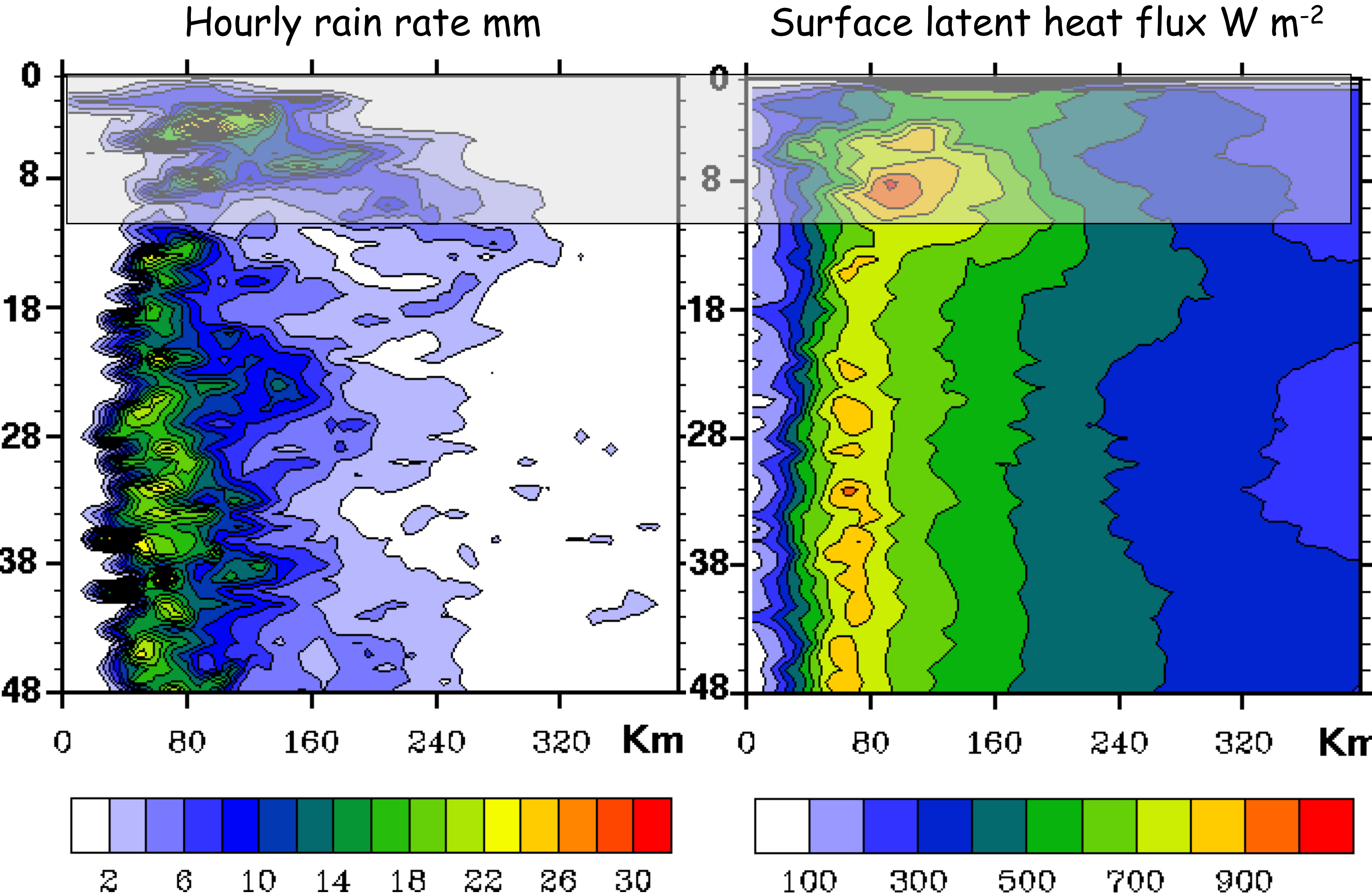
Hurrican Ivan SST: 11 Sep - 16 Sep 2004



Hurricane Ivan: 48 hour simulation: Starting 13 September 00Z



Hurricane Ivan: 48 hour simulation: Starting 13 September 00Z



700 W m^{-2} ≈ 1 mm/hr

Hurricane IVAN: September 13, 2004:

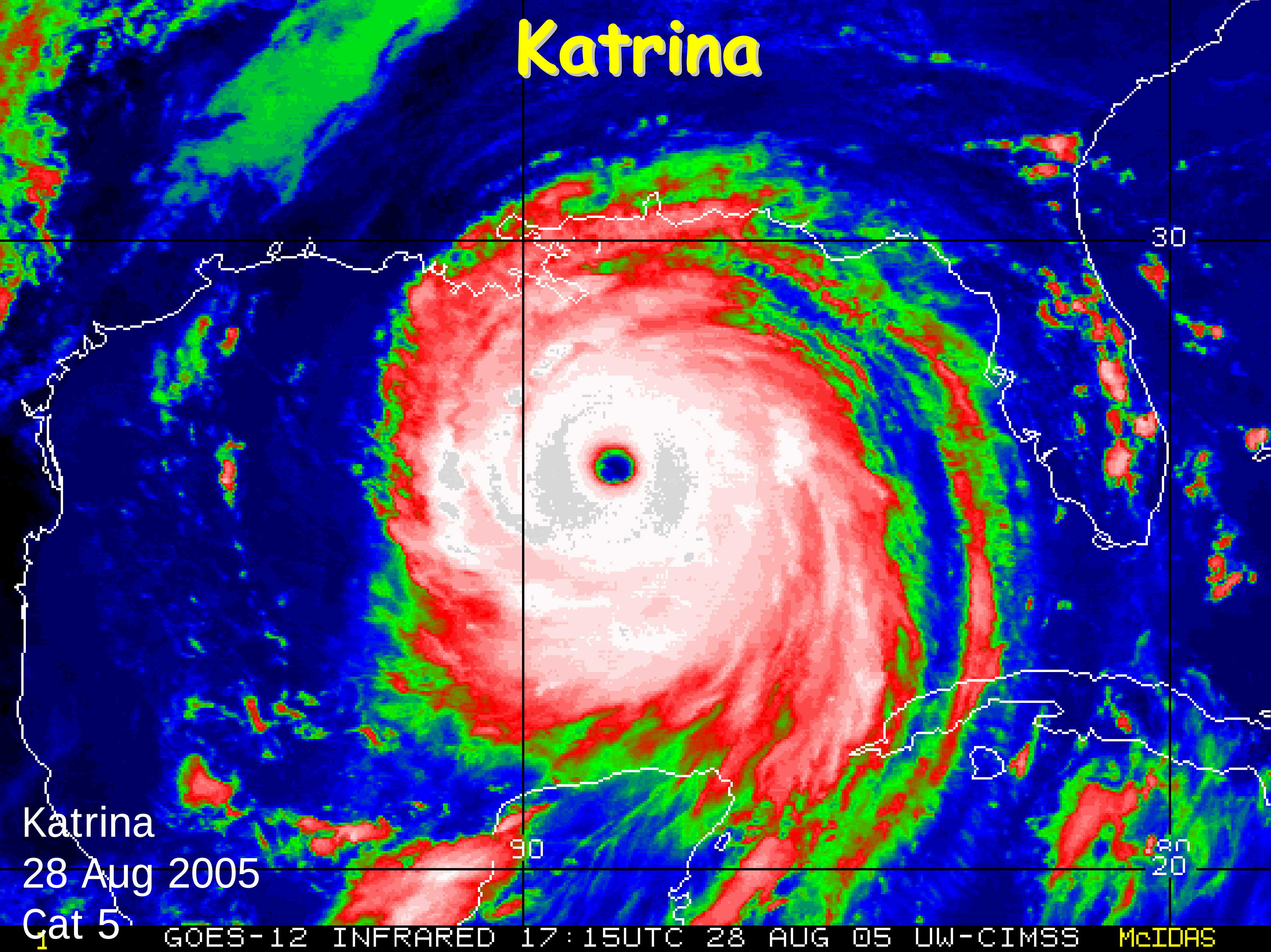
48 forecasts with WRF @4km resolution
Hours 30-42 (0600 to 1800 14 September 2004)
Integrated

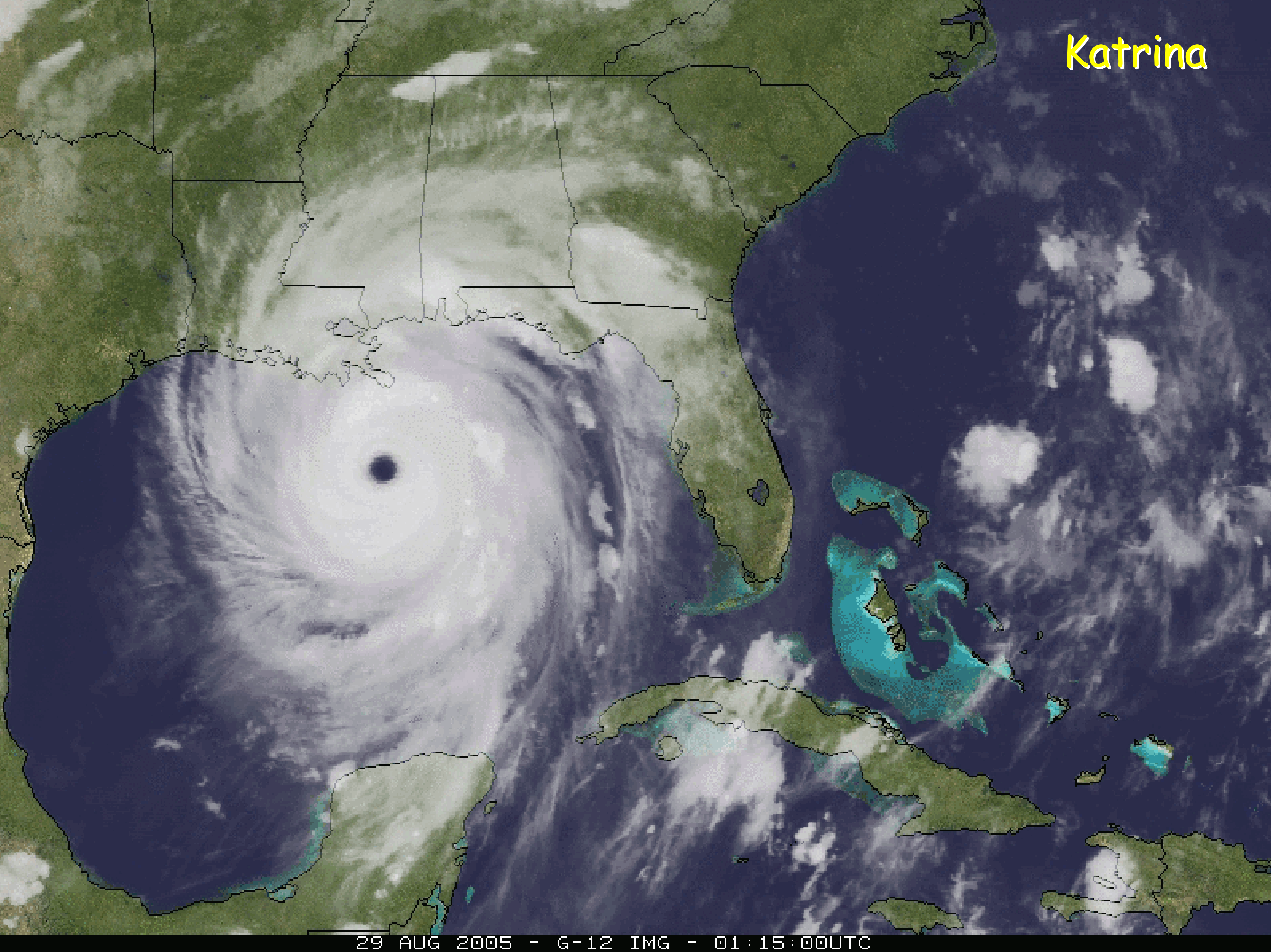
	0-100 km	0-400 km
Wv Transport	12.4	2.12
Precipitation	13.4	2.97
Surface L Heat Flux	1.04	0.60

Ratio Precip/LH 12.9 4.95

All fields in units of mm/h (696 W m^{-2})

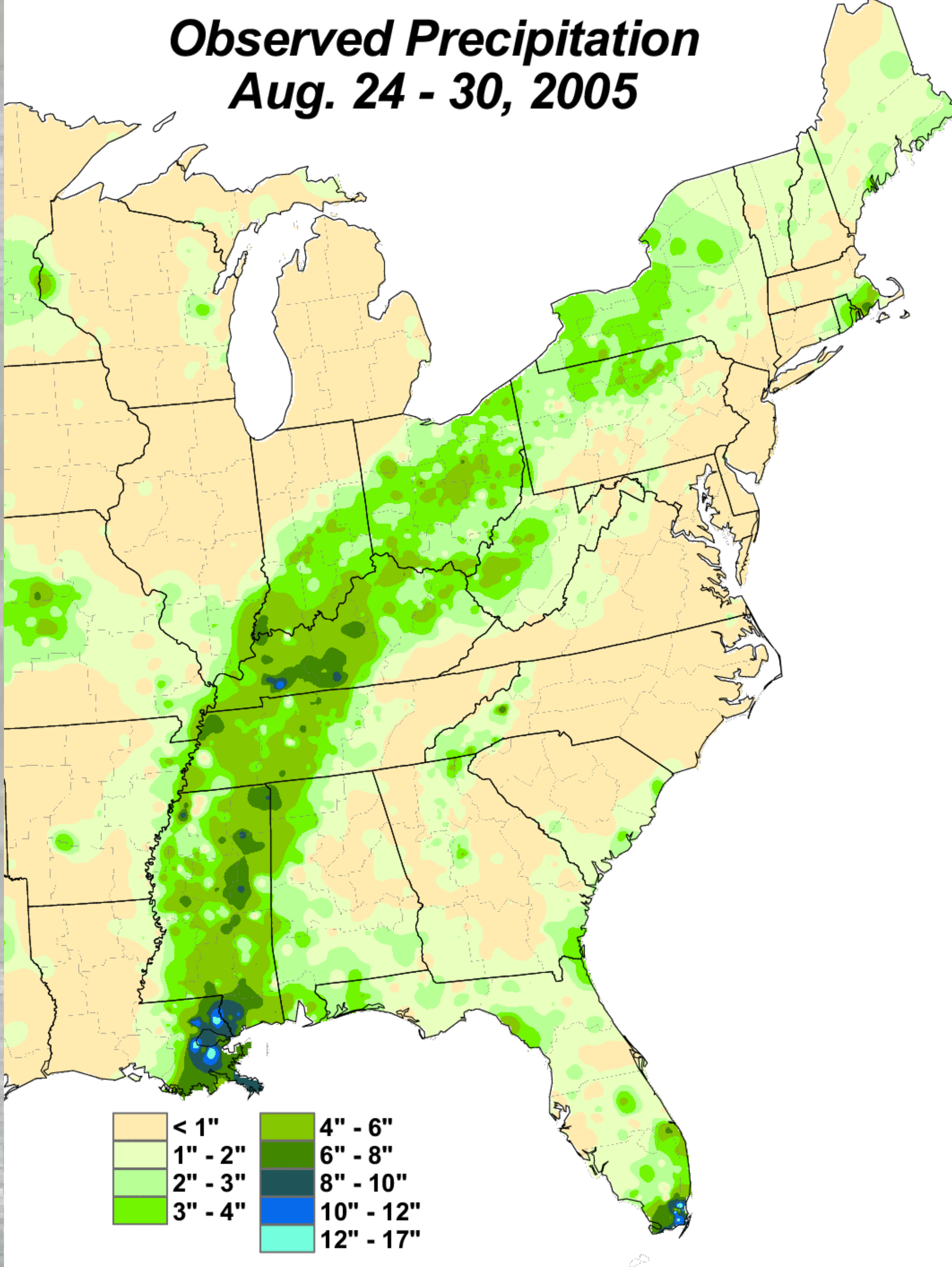
Over 400 km, 2.9 mm/h = 1 PW.


Katrina
30
90
20
Katrina
28 Aug 2005
Cat 5
GOES-12 INFRARED 17:15UTC 28 AUG 05 UW-CIMSS McIDAS


Katrina
29 AUG 2005 - G-12 IMG - 01:15:00UTC

Katrina's aftermath

Refugees in USA Aug 31 ⇒



Katrina Precipitation

Based on only surface reports (no radar)

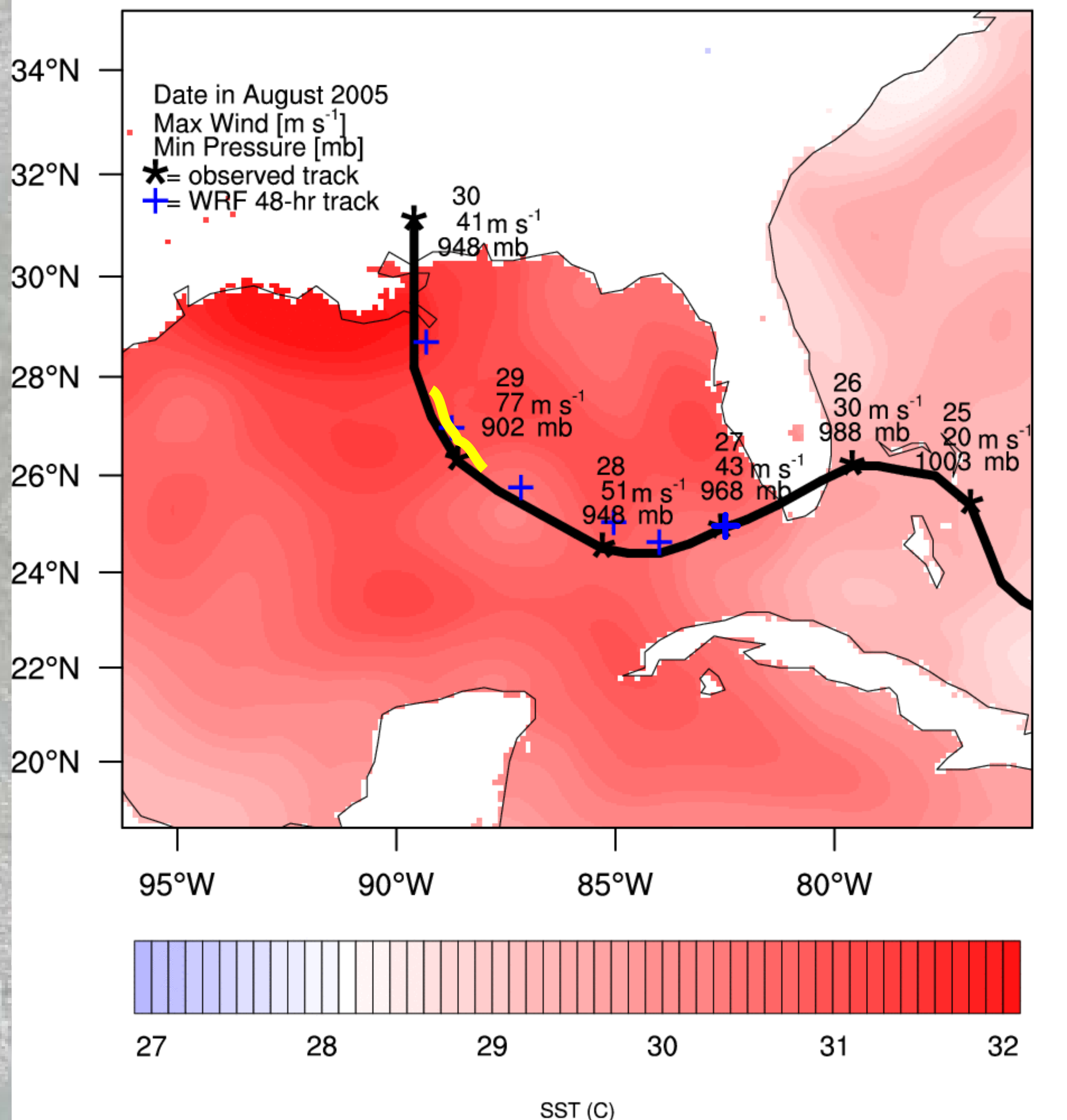
Courtesy: Rich Tinker, CPC, and NCDC NOAA

Katrina experiments

- Given good track forecasts of Katrina, as well as the diagnostics of the energy and water budgets, we rerun the forecast simulations with SSTs changed by +1°C and -1°C
- The control run has the central pressure 892 mb vs observed 902 mb
  - +1°C: 870 mb: -22 mb
  - -1°C: 910 mb: +18 mb

  - Max winds 58 m/s (-1) go to 70 m/s (+1)
  - Order 10% per C

Hurricane Katrina WRF SST: 27 Aug 2005

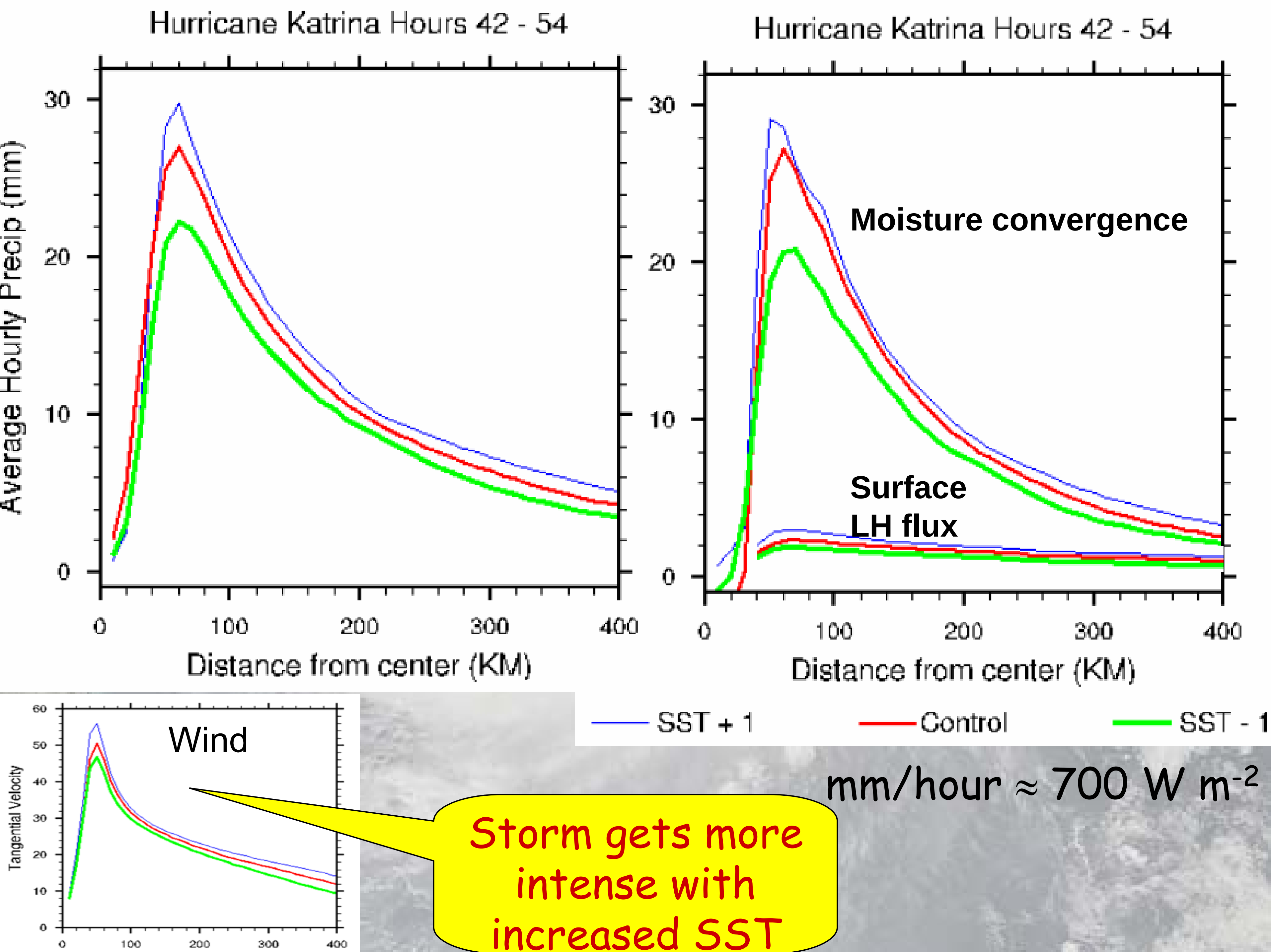


Katrina

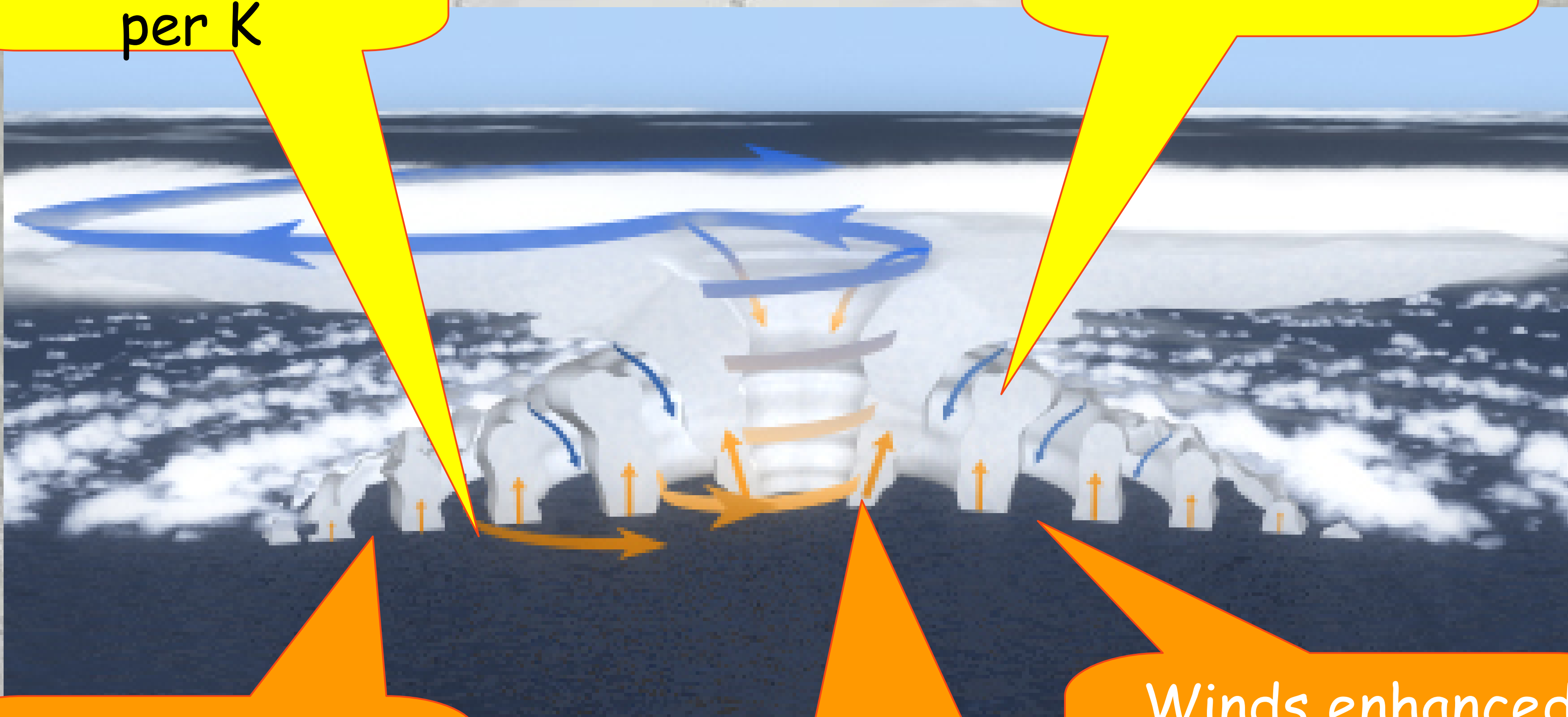
Observed and WRF simulation

Katrina

- **Ratio of rainfall to surface LH flux is 9** inside 100 km, and **3.9** inside 400 km. They are comparable at 700 km and a balance is achieved only by considering a radius of about **1600 km.**
- This highlights the **major role of moisture convergence by the low level (below 1 km) inflow** into the storm.
- That convergence in turn is driven by the surface LH flux, latent heating and storm circulation.
- Nonetheless it highlights the role of the large-scale environment in these storms.


Hurricane Katrina Hours 42 - 54
Average Hourly Precip (mm)
Distance from center (KM)
Hurricane Katrina Hours 42 - 54
Moisture convergence
Surface LH flux
Distance from center (KM)
Wind
Tangential Velocity
SST + 1
Control
SST - 1
mm/hour ≈ 700 W m-2
Storm gets more intense with increased SST

Changes in Hurricane 0-400 km



Surface LH flux enhanced 25% per K

Rain enhanced 19% per K

Inflow enhanced 17% per K beyond 280 km

Eyewall peak winds enhanced 9% per K

Winds enhanced 10-18% per K well outside eye

How big is the effect from global warming?

Since 1970 tropical SSTs have increased 0.5°C
And water vapor has likely increased ~3.9% at each point.
This means increases in rainfall and latent heat release in storms by order 7% [4 to 12%].
[1" extra rain near New Orleans in Katrina]

The added rainfall and resulting flooding could be enough to breach levees designed without accounting for global warming.

Implications for climate models

1) In models, the thunderstorms and **convection are not resolved** and are dealt with by "**sub-grid**" scale parameterization.
2) However, most (all?) climate models have **premature onset of convection**, as seen in the diurnal cycle over land, and feature convection too often and with insufficient intensity.
3) This characteristic likely means that sub-grid scale **convection is overdone** at the expense of organized convection (MJO, tropical storms etc).
4) Hence models likely **under-predict** changes in hurricanes.
5) **Hurricanes are missing in models**: SSTs may get too warm: increased TCs keep SSTs cooler.